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Periodic urban models for optimization of passive solar irradiation

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ABSTRACT

Urban sprawl and energy consumption issues suggest to consider how to design energy efficient dense cities. Solar radiation is a significant heat input in well insulated buildings in temperate climates. However, the solar masks generated by the surrounding buildings in dense urban areas can reduce significantly this energy gain. This paper proposes a definition of a district as a periodic urban fabric, where a given configuration of buildings, called *urban cell*, is repeated to represent the urban outline. It allows us to evaluate the relationship between cumulative solar potential on façades and urban shape, with solar masks that are consistent with the considered area. In this study, an evolutionary algorithm is used to explore the set of urban cells composed of a square grid of blocks of varying height. Four conditions for solar radiation are taken into account: clear sky direct radiation at the latitude of 50° North for three particular days (winter solstice, summer solstice and equinox), and annual direct and diffuse radiation based on the meteorological data of Paris, France. For each condition of solar radiation, the influence on the optimization results of the size of the area of interest and its built density is assessed. The results provide information on what are the urban shapes maximizing solar potential and give some quantitative indications on the amount of solar radiation that can be captured.

1. Introduction

Solar radiation is a significant heat input in well insulated buildings in temperate climates. In dense urban area however, buildings cast shadows to each other, reducing the available energy during the heating season. For this reason, the shape of the city is a relevant feature to be studied with respect to the amount of solar radiation it can capture.

Two major approaches have raised in the litterature to tackle this topic. The first one consists in the evaluation through simulation of the solar potential of real cities. This gives a specific knowledge for the studied city. In this manner, the cities of Geneva, Switzerland, and London, United Kingdom, have been studied respectively with CitySim and with the solar radiation tool of ArcGis together with Ecotect (Mohajeri et al., 2016; Sarralde et al., 2014), with the objective to relate the various district morphological features such as density, plot ratio, or site coverage and solar potential.

The second approach consists in using simplified, standard geometry of buildings and districts to assess their quality. Following this approach, efforts have been made to understand through parametric studies the best geometrical characteristics for solar radiation or energy consumption related criteria of theoretical urban shapes like urban canyons (Strømann-Andersen and Sattrup, 2011), courtyards (Muhaisen, 2006), urban blocks (Ratti et al., 2003) or residential neighbourhoods (Hachem et al., 2013).

From the second half of the 2000 decade, optimization methods have been increasingly employed in the field of sustainable building design (Evins, 2013; Stevanović, 2013), although few papers actually tackle the solar access problem at urban scale. This methodological step opens large capability of exploration adapted to problems with multiple variables, and is often employed in simplified geometric studies of the urban shape.

Kämpf and Robinson (2010) showed in a solar potential optimization study using meteorological data of Basel, Switzerland, that a significant improvement in overall solar energy on facades and roofs can be achieved by changing the height of buildings. This potential gain has also been corroborated in clear sky radiation potential optimization studies involving height, rotation and translation parameters for building modifications (Oliveira Panão et al., 2008; Vermeulen et al., 2015). The relationship between urban block shape and annual heating needs has also been confirmed through the optimization of a simplified urban block of Paris, using the exploration capability of the

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evolutionary algorithm (Vermeulen et al., 2013).

Martins et al. (2014) performed an optimization of the shape of a district in Maceió, Brazil, based on representative urban typologies defined from an analysis of the built urban fabric. Given the considered geographic location, the objectives were to maximize solar potential on roofs (for solar panels) while minimizing the solar potential on façades (to avoid overheating). The optimization results were then related to morphological urban features such as floor area ratio, plot ratio or aspect ratio.

Kämpf et al. (2010) studied the optimal shapes for a block of the district of Basel, Switzerland considering irradiation offset by thermal losses. In this work, possible locations for buildings were pre-defined within a fixed urban context, while the optimization variables were related to the height of buildings and the shape of their rooftops. The results show the importance of density built on energy results for the best configurations found.

In this paper, we propose a geometric representation of the city as a periodic urban fabric in which the basic element, called urban cell, is repeated in each direction, producing solar masks to itself. The periodic characteristic of the urban fabric allows us to draw comments on the urban shapes verifying that the surroundings remain consistent with the area of interest as it is being modified, in opposition to pre-determined context or open area districts.

This representation is then used for the optimization of a district where buildings have variable height using an evolutionary algorithm. The objective is to perform a guided search aiming at understanding what are the best and worst urban shapes as well as the potential of improvement of various solar radiation related criteria.

In a first section, the definition of the periodic urban fabric is given. A test case of periodic urban shape optimization is then described, and regular urban typologies for different cell sizes are defined for comparison purposes. The objective functions and optimization algorithm are explicited later. Finally, the results of optimization are presented and commented in both morphological and quantitative ways as a function of the criteria, the built density, and the size of the area of interest.

2. Description of periodic urban fabric representation

2.1. Definition

The periodic urban fabric is defined by the repetition of a pattern – the tile of the periodic tiling –, called in this context *urban cell*. Thus, the buildings included in the urban cell appear periodicaly in the representation of the district. The fabric in itself is an infinite reproduction of the urban cell in each direction. A parallel could be made between this definition and the cyclic boundary conditions widely used in computational fluid dynamics, and implemented in software tools for urban climate simulation such as ENVI-MET (Bruse, 2004).

In the following, we use the urban cell in a representation of the city as a set of square-based buildings of varying height centered on parcels arranged in an orthogonal grid. It should be noted that, although urban cells are square in the present study, their definition could be successfully derived to represent a variety of urban shapes that observe translation symmetries (canyons, courtyards, etc.). An example of urban cell of dimensions 3 × 3 is shown in Fig. 1. On this figure, the urban cell is repeated once, but its repetition should be considered as infinite from our definition.

2.2. Practical implementation for solar radiation simulation

In the present work, the periodic urban fabric is used for a study of solar energy maximization. While we define the periodic fabric as an infinite reproduction of an urban cell, in practice, this reproduction is limited to control the balance between computation time and solar potential simulation precision. For this reason, the evaluation is performed separetly for each building, considering solar masks in a predefined radius around the evaluated building. This radius is called *radius of reproduction* and represents the number of strips of parcels considered in each direction from the point of view of the building which solar potential is computed. An example of generated geometries for two different buildings of a 3 × 3 cell is presented on Fig. 2.

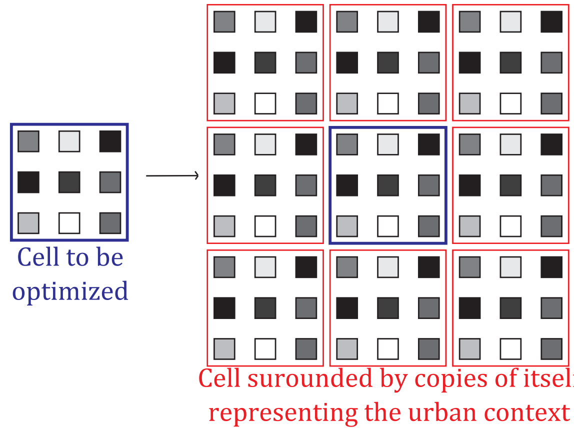

Fig. 1. Urban cell representation. The height of the buildings is represented by grey levels.

This method guarantees than any two different urban cells generating the same urban fabric have the same value of objective function, and that the evaluation of a configuration does not depend on the cell size (for small urban cells, several repetitions of the cell are necessary to reach the desired radius of reproduction). Similar approaches can be found in simulation methods designed for the evaluation of sky view factors on large urban models (Muñoz et al., 2015), or the simulation of daylight on large urban scenes using distance-dependent level of detail of the geometry (Besuievsky et al., 2014).

3. Methodology

In this section, urban shape optimization methodology is developed. First, the geometric features and design variables of a test case are presented, together with a typology of urban fabrics defined for analysis and comparison purposes. Then, the solar radiation evaluation method and the optimization criteria are described. Finally, the optimization method is introduced.

3.1. Case study

3.1.1. Dimensions and parametrization

In the proposed case study, the urban cell is a square grid of $p \times p$ parcels. Each parcel is a square of dimensions 20 m × 20 m in the center of which is located a building of base 10 m × 10 m (*cf*. Fig. 3).

The height of each building i, $i = 1,\dots,n$ is defined by the integer x_i corresponding to its number of floors of 3 m height. Possible building height values range from 0 m to 30 m. Thus, we have:

$$x_i \in \{0,1,\dots,10\}, \quad i = 1,\dots,n$$

The vector of variables is defined by:

$$\vec{x} = \{x_1,\dots,x_n\}$$

In order to compare districts with similar total building envelope area, a constraint on the total volume to be built, $\overline{V}$ is imposed:

$$\sum_{i=1}^{n} 3x_iA_i = \overline{V} \tag{1}$$

where A_i is the floor area of building i.

Various optimization cases are then defined: